October 17, 1995

CONTRACT NAS8-38856

Structural Damage Prediction and Analysis for Hypervelocity Impact

Consulting

LOCKHEED MARTIN

MAF/MMA 31-100 (3/95)

HYPERVELOCITY IMPACT STUDY CONSULTING

FOREWORD

A portion of the contract NAS8-38856, "Structural Damage Prediction and Analysis for Hypervelocity Impacts," from NASA Marshall Space Flight Center (MSFC), included consulting which was to be documented in the final report. This attachment to the final report contains memos produced as part of that consulting. The Technical Monitors were Joel Williamsen, Greg Olsen, and Jennifer Robinson. Consulting was performed between October, 1990 and September, 1995.

TABLE OF CONTENTS

Subject: Critical Flaw Size in a 2219-T87 Tank   Date: October 3, 1990

Given Conditions:

Geometry:......Cylinder   Material 2219-T87

Diameter......50   inches   Pressure.........313   psi

Thickness.....0.175 inches   Stress Level.....44.7   ksi

Length 60   inches   Temperature...Ambient

Analysis Results

Geometry - FLAGRO Solution Number	Diameter [in]	Toughness Kc [ksi·√in]	Critical Flaw [in]
Surface Crack in a Flat Plate 12 inches Wide - SC01	Infinite	30	a = 0.15 2c = 0.30
External Surface Crack in a Pipe Longitudinal - SC03	50	30	a = 0.14 2c = 0.28
Through Crack in Pipe Longitudinal - TC07	25	54.3	2a = 0.77 thru
Through Crack in Pipe Longitudinal - TC07	50	30	2a = 0.28 thru
Through Crack in Pipe Longitudinal - TC07 *This is the recommended case.*	**50**	**54.3**	**2a = 0.82 thru**

Notes:

Through flaw length = 2a

Surface Flaws were assumed to be semi-circular.
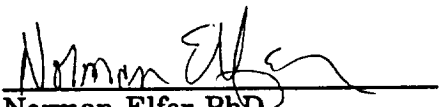
      a = depth   2c = total length at the surface

CRITICAL FLAW SIZE CALCULATIONS - NASA/FLAGRO compiled on a Macintosh was used for all calculations. (See attachments.) However, the surface flaw solutions were modified by Martin Marietta Manned Space Systems to give the critical flaw size when the stress intensity at either the depth, a, or the surface, c, exceed the toughness. The original FLAGRO program calculated the critical flaw size based on only the depth. The
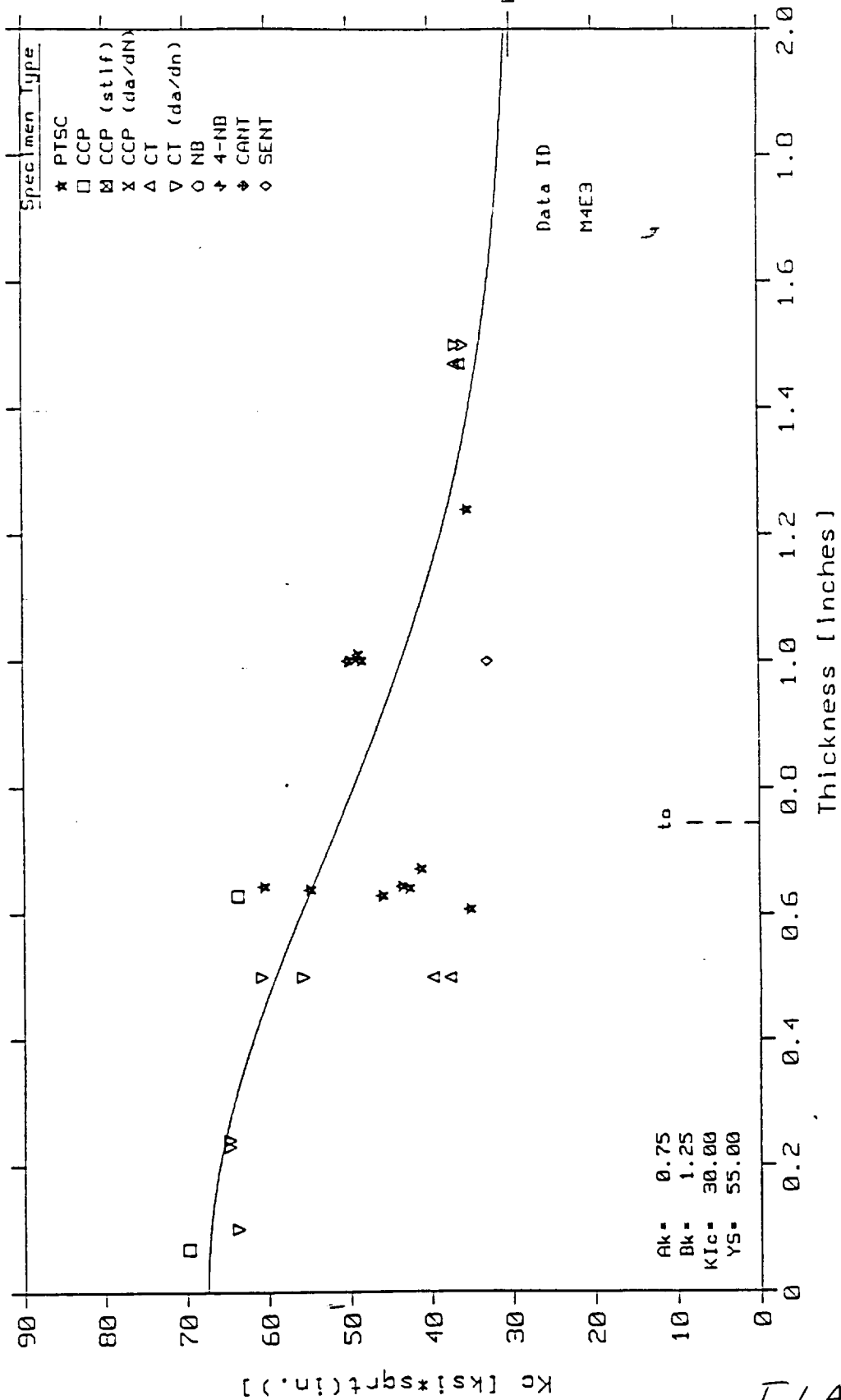
page 1

modified program will give a smaller flaw size for those situations when the stress intensity is higher at the surface. This is not a very significant effect for semi-circular flaws in pure tension.

TOUGHNESS - The toughness of 54.3 ksi was calculated by FLAGRO for the thickness of the cylinder. This is consistent with experimental observations. (See Attachments for representative flaws that fail at similar stresses. eg. for thickness = 0.188 [all dimensions in inches] , width = 3.91, and an initial flaw size of a = 0.118 and 2c = 0.714 the fracture stress was 48.5 ksi.) Reducing Kc to 30 ksi$\sqrt{in}$ for impact conditions is not recommended for 2219-T87. Hopkinson bar tensile tests on 2219-T87 show that both the strength and ductility increase at high strain rates. High strain rate behavior often correlates with cryogenic behavior. Cryogenically 2219-T87 has higher strength, ductility and toughness than at room temperature. (This is not true for all aluminum alloys.) The material is therefore expected to be tougher under impact than under static conditions.

CRITICAL IMPACT - If the higher toughness is correct as recommended, then this implies it is possible to leak without rupture. Impact craters which do not exceed the thickness may still cause a penetration by spalling the remaining thickness. (A rough approximation for a leak threshold is a crater depth of 70 percent through the thickness.) However, if the impact crater depth exceeds the thickness of the pressure wall, significant energy will be deposited in the contents. If an incompressible fluid is present on the other side of the wall, high pressures will cause the wall to tear. A conservative assumption is that cracks will run to the critical length and then propogate due to internal pressure. On the other hand, if a compressible vapor is present, then a hole even larger than the critical flaw size may be acceptable. However, for a hole that size, failure of the opposite wall may be the more likely failure mechanism.

Analyst: _____

Norman Elfer PhD.
Program Manager
Hypervelocity Impacts Study

page 2

Kc [ksi*sqrt(in.)] vs Thickness [Inches]

Specimen Type
★ PTSC
□ CCP
⋈ CCP (stlf)
✕ CCP (da/dN)
△ CT
▽ CT (da/dn)
○ NB
✦ 4-NB
✚ CANT
◇ SENT

Data ID

M4E3

Ak = 0.75
Bk = 1.25
KIc = 30.00
YS = 55.00

2219-TB7 AL, L-T, 75F

FLAGRO

216

Norman Elfer   9:13 PM

CTV - Ti-6Al-4V

Pressure Vessel   NASA-FLAGRO
D = 50 inches
p = 313 psi
S = 86.9 ksi
t = 0.090 inches

Kc [ksi·√in] vs. Total Crack Length (2a or 2c) [inch]
Through Crack TC07 / Surface Crack SC03

TC07 — Thru Crack in a cylinder D=50 inches

Kc	a	2a
30	0.0374	0.0748
40	0.0658	0.1316
50	0.1012	0.2024
60	0.1430	0.2860
70	0.1901	0.3802
80	0.2415	0.4830
90	0.2963	0.5926
100	0.3530	0.7060

SC03 — Surface Crack (External) in a Cylinder D=50 inches

Kc	a	2c	a/t
30	0.0478	0.0956	0.53
35	0.0583	0.1166	0.65
40	0.0682	0.1364	0.76
45	0.0775	0.1550	0.86

SC01 — Surf Cracked F W=12 inches

Kc	a	2c	a/t
30	0.0524	0.1048	0.58
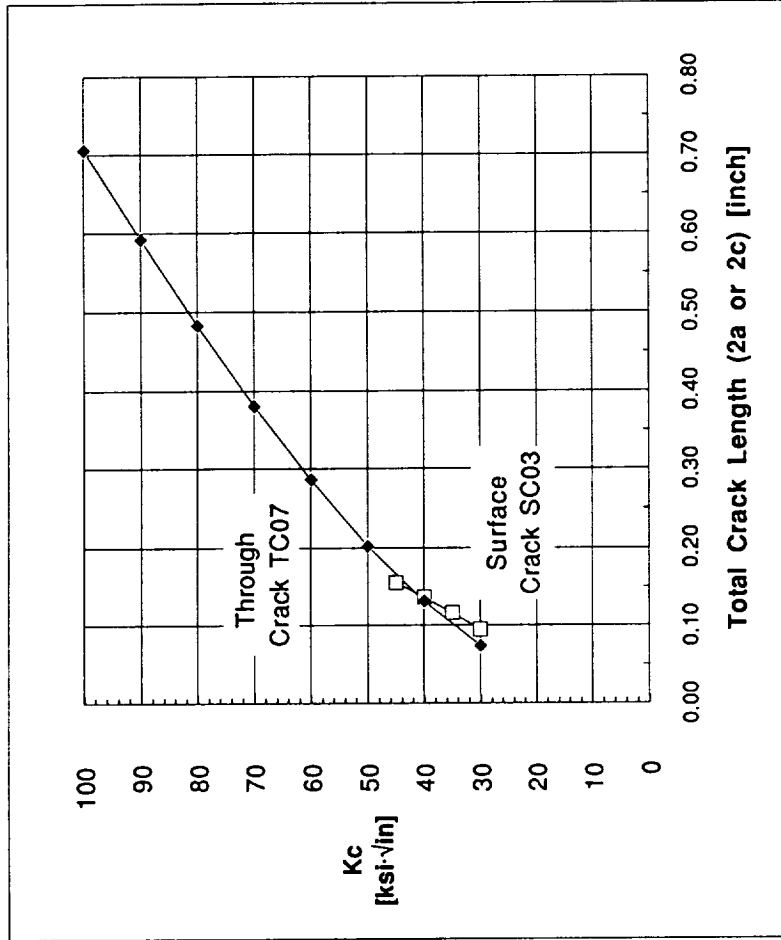
A Preliminary and Informal Analysis of Meteoroid/Debris CR Impacts

Reference: Meteoroid/Debris Change Requests 869A and 883A

Question 1: Will subject designs meet projected ballistic limit curves?

- The curves appear to meet the ballistic limit equations proposed by Eric Christiansen. (Selected points were checked. A complete check is in progress.)

- The total areal density and spacing for the BL curves given is consistent with results achieved by multi-shock (MS) shields, but I suspect that more refinement of the MS shield will be required to achieve these BL curves at such large debris sizes. (Refinements/optimization include number of layers, spacing, mass distribution within layers, etc.) This could influence attach structure complexity and weight, but this would be a less significant effect.

Question 2: Will curves used result in probabilities projected?

- This was not checked yet, but the analysis is presumed correct.

- Did the analysis consider variations in pitch atitude?
  - A pitch of +30° to +36° when the Shuttle is attached (assumed to be 10% of the time) could severely decrease the PNP.

Question 3: Are there better ways to perform the design?

- The NEXTEL MS shield has the lowest areal density of any shield system for direct impact of aluminum projectiles in the 1 cm size range. However, it also has the largest spacing requirements.

- A bumper designed to cause "ricochet" may be an alternative to the MS shield. Increased secondary debris flux could be a hazard. The shield sizing will be analyzed in more detail.

- Collision avoidance (CA) should be used and accounted for in the analysis. The attached figure shows the effect of CA on the flux of debris. The figure assumes 100% avoidance of 10 cm and larger debris. For the same flux level (Probability of No Impact) the debris diameter can be reduced from 4 to 2 centimeters in diameter. A more detailed analysis on the overall PNP is possible. It can include variables in debris detection, Probability of No Failure of the CA system, etc.

- The module wall and shield design should be changed to prevent Crit. A failures.
  - The module wall waffle (integrally machined stiffener) spacing should be reduced to prevent either a hole which could cause too rapid de-pressurization, or a crack which could cause catastrophic rupture. A 7 inch spacing would probably be adequate, but a 5.25 inch spacing would almost

certainly prevent a Crit A failure. (It is assumed that a 6 inch diameter hole is the limit for de-pressurization. This analysis depends on operations, final design, ECLSS, etc. and should be provided by BAC.)
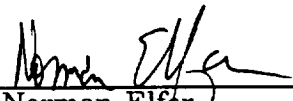
- Additional stringers could add significant weight to the module. To maintain the same weight, the additional crack stopper stiffeners could be limited to a height of 0.75 inches and the rear wall reduced in thickness to 0.105 inches. A larger shield spacing, and ballistic blankets would more than make up for the loss in rear wall thickness. The required thickness and height of the crack stopping stiffeners has not been calculated yet. This is based on ROM estimates of the effects of stiffeners on the stress intensity in a cylinder. Detailed NASTRAN analyses will be conducted for the Handbook.

- If a deployable or erectable shield must be used, then the standoff should be so large as to prevent momentum/Wilkinson failure. The NEXTEL MS system described by Christiansen reportedly will exhibit momentum failure above 6 km/s. Even though large standoffs are used, the low areal density of each shield does not spread the debris over a large area. The spay area on the rear wall is so small that bulging and tearing can occur. Extrapolation above 7 km/s is not very clear if larger spacings are used. Hydrocodes are limited by the large spacings and lack of good material models for cloth. As a conservative estimate, the BL for fragment penetration should be kept constant above a normal impact velocity of 6 km/s.

It is suggested that the minimum spacing should be **twice** the spacing which causes rupture at approximately 7 km/s. This would provide protection from momentum rupture due to a particle twice as massive and twice as fast as can be tested with current two stage light gas gun technology. Larger particles would not be fully shattered by the bumper system and would not deposit their full momentum in the rear wall.
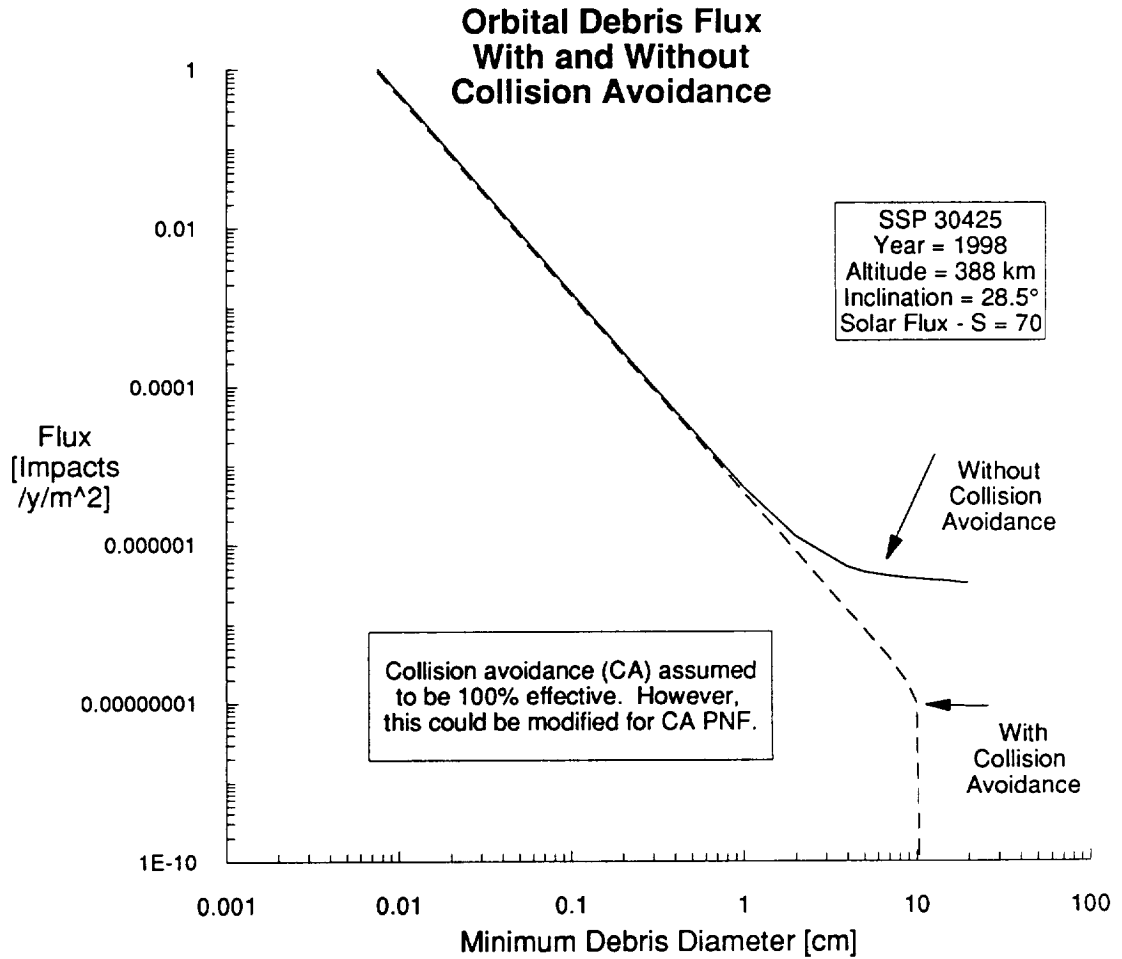
The effect of obliquity on momentum failure is not well documented. A conservative approach has been to use only the normal component of momentum (Wilkinson and Cour-Palais/Crews/Christiansen). The equations should be modified to account for larger effective spacing for oblique impacts.

Further analysis is in progress for inclusion in the Handbook.

- A complete design incorporating all of these features is not available at this time.

Norman Elfer
Hypervelocity Impacts Study
Program Manager
(504) 257-3162

Structural Damage Prediction and Analysis for Hypervelocity Impacts

**Orbital Debris Flux
With and Without
Collision Avoidance**

SSP 30425
Year = 1998
Altitude = 388 km
Inclination = 28.5°
Solar Flux - S = 70

Flux
[Impacts
/y/m^2]

Without
Collision
Avoidance

Collision avoidance (CA) assumed
to be 100% effective. However,
this could be modified for CA PNF.

With
Collision
Avoidance

Minimum Debris Diameter [cm]

Martin Marietta - Manned Space Systems

MARTIN MARIETTA MANNED SPACE SYSTEMS

PO BOX 29304
NEW ORLEANS LOUISIANA 70189

Date: April 30, 1993   4150-HVIS-93-1

To: G. Olsen   NASA-MSFC ED52
        C. Finnegan   NASA-MSFC ED24
        J. Newman   NASA-LaRC 188E
        R. Forman   NASA-JSC ES5
        H. Neid   GE CR&D
        W. Bachrach   GE CR&D
        D. Williams   Boeing Huntsville

From: N. Elfer

Subject: Fracture Toughness of 2219-T87

Attachment: a) Boeing Process Specification Departure PSD 5-1 to Process
                 Specification BAC 5602, dated 2/13/63

             b) Boeing Process Specification Departure PSD 5-1 coordination sheet
                 from Bob Sands, dated 2/12/1963, describing the rationale for BAC
                 5602 PSD 5-1.

             c) Boeing direction to a vendor dated 2/11/63, describing the before
                 and after condition in BAC 5602 PSD 5-1.

             d) Memo dated 2/11/74 from Bob Gerdetz, ALCOA, to Pete Hinkeldey,
                 Martin Marietta (proprietary pages on capability withheld)

References: 1) "Damage Tolerant Design Handbook," J. P. Gallagher, ed. Battelle
                 Metals and Ceramics Information Center MCICHB-01R, 1986.

             2) Eichenberger, T. W.: "Fracture Resistance Data Summary,"
                 Report DA-20947, 1962. (as referenced in reference 1)

             3) Elfer, N.: "Fracture Toughness Comparison," Martin Marietta
                 Manned Space Systems, IRAD M-01S, 826-2370, 1987

The fracture toughness of 2219-T87 has come into question in the damage tolerance analysis of Space Station Freedom modules. In particular there was a significant difference in the plane stress fracture toughness (K_c) quoted in References 1 (derived from data in ref. 2 which was published in 1962) and the plane stress fracture toughness quoted in References 3 from 1987. The 1962 data indicated a K_c of approximately 100 ksi√in based on an initial total flaw size (2c) of eight inches in 0.1 inch thick sheet. There was also a flaw size dependence typical of R-curve effects, such that shorter flaws had lower toughness and larger flaws showed an even higher fracture toughness. In contrast, the 1987 data showed only a 65 ksi√in K_c based on initial flaw lengths (2c) of four to 10 inches in 0.125 inch sheet. There have been suggestions that this difference may be due to test method. This letter notes there was a difference in heat treatment between the two sets of specimens, and that may outweigh any differences in the test procedure.
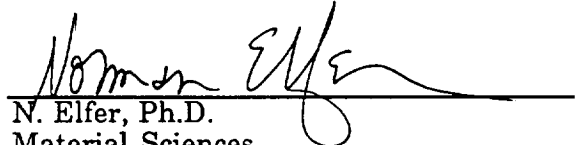
It was first thought that the difference in toughness was due to differences in anti-buckling restraints used during testing. Reference 1 notes the existence of anti-buckling restraints in the 1962 test report, but it does not detail the fixturing used. It has been postulated that the anti-buckling restraint consisted of plates on either side of the specimen, with a machined slot to observe the crack, very close to the crack tip. In the 1987 test program, C-channel sections were used on both sides of the specimen, one to two inches above and below the crack plane. Polyethylene pads, 0.25 inch thick, were placed between the C-channels and the specimen. Don McCabe at Oak Ridge National Lab, chairman of the ASTM sub-committee on R-curve testing, was contacted, and he stated a strong preference for the latter (1987) method of anti-buckling restraints. He felt the separate stiffeners were adequate to stop buckling, and would not risk picking up some of the load.

Lacking details about the test program reported in 1962, it was also postulated that the gage length between the grips/dogbones might not meet ASTM recommendations of 1.5 to 2 times the specimen width. However, finite element analysis has shown that a gage length of 0.8 times the width would not have a significant effect (less than 5%) on fracture toughness. Therefore, this could not explain the large disparity in reported toughness.

If the test method is not responsible for the difference in toughness, then there should be an explanation why the material was different between the two test programs. Old Saturn files (attachments (a) through (c)) at the Michoud Assembly Facility showed that the Boeing process specification for aging 2219-T37 to the -T87 condition changed in 1963 from 14 hours at 325°F to 24 hrs at 325°F ± 10°F. The change in the heat treatment was to ensure that there were no stress corrosion concerns. Stress corrosion of 2219 was known to be an issue in thick sections in the underaged condition, or peak aged condition at low aging temperatures. It was also known that by aging 2219-T37 at 300°F even better mechanical properties could be achieved, again at the expense of stress corrosion susceptibility in thick sections.

The aging curves for 2219-T87 (Fig. 7 in attachment d) predict that there are no significant differences in mechanical properties between aging 14 versus 24 hours at 325°F, but it can also be seen that ductility increases significantly at lower aging temperatures, 300°F, or with shorter aging times. The specimens referenced in the 1962 report may have had an improved toughness associated with higher ductility from either (1) aging at the low side of the 315° to 335°F temperature range, (2) purposefully aging at 300°F, or (3) having material with slightly slower aging kinetics due to chemistry or processing.

This strongly supports the current effort to test specimens that are heat treated using the same procedures that will be used for SSF. The aging curves (attachment (d)) show that ductility should not decrease using SSF's 375°F age forming temperature instead of 325°F, but a slight reduction in tensile strength may occur, which would be reflected in reduced toughness.

N. Elfer, Ph.D.
Material Sciences
Martin Marietta Manned Space Systems
PO Box 29304 Dept. 4150
New Orleans, LA 70189
Ph.:(504)257-3162 FAX:(504)257-4404

PROCESS SPECIFICATION DEPARTURE	ORIG. R. R. Sands	PSD NUMBER 5-1	PROCESS SPEC. NO. BAC 5602
	SUPV. W. G. Smith	PG 1 OF 1	

☐ OPTION   ☒ REQUIREMENT

MFG.

☐ DEVIATION   ☐ VARIATION

QUAL. Harry Anderson

REASON To furnish process
heat treatment of 2219-T37 to
2219-T87 plate.

MAT'L O. E. Carlson

NASA REP.

FROCESS SPEC. TITLE

**HEAT TREATMENT OF
ALUMINUM ALLOYS**

M. Kalemeoff 2/13/63

ENGR. APPROVAL   M. L. Koehler

2-13-63
REL'S DATE

BUB CONTRACTOR(B) AFFECTED	ON MODELS	MFG. DEPTS. OF DIV. BELOW AFFECTED
All	C-5 and S-1C	All

4.2.5.2 ADDITIONAL PRECIPITATION TREATMENTS

Alloy	Final Temper Designation	Original Temper Designation	Treatment	
			Temperature	Time
2219 Sheet and Plate	T-87	T-37	325 $\pm$10°F	24 hours

COORDINATION SHEET

TO H. G. Anderson 5-4200 LJ-47

NO. 5-7512-M-3CS-1004

ITEM NO.

GROUP INDEX Materials and Processes Unit,
Standards and Specifications Group

DATE February 12, 1963

SUBJECT Boeing Material Specification BMS 7-105B

MODEL SATURN

REFERENCE: (a) Memo 5-4200-M-19, January 21, 1963, same subject.

(b) BAC 5602

The 24 hour age called out in BMS 7-105B is a Vendor initiated heat treatment to improve the stress corrosion resistance of 2219-T87 Aluminum. This aging treatment is, at the present time, being coordinated for inclusion in MIL-A-8920 and MIL-H-6088.

BAC 5602 still calls out a 14 hour ageing treatment for T-37 to T-87 material but since NASA will accept only 24 hour aged material we have issued P.S.D. #5-1 of BAC 5602 which calls for a 24 hour age on sheet and plate for 2219-T37 to T-87 cond.

Prepared by _____
R. R. Sands

Approved by: _____
M. L. Koehler

cc: L. E. Buchart 5-7100 LH-41
R. Hinkley 5-7620 A3-78

Bob SANDS Attachment C

Feb 11 - 2 21 PM '63

DEWIC C314

124PM CST

3 STA 314 NORMAL
N STA 274 NOR 015 NEW ORLEANS 2-11-63 1:33PM CST 63

DI PAUL A KINSLOW 5-7512 WK-CC
X MASD DIVISION, WICHITA BRANCH EXT 444

OBJI HEAT TREATMENT OF 2219-T37 AL PER BAC 5602

-7512-M-1T-054

EAT TREAT 2219-T37 SHEET AND PLATE TO 2219-T87 CONDITION BY USING
25 DEGREES F. TEMPERATURE FOR 24 HOURS INSTEAD OF THE 14 HOURS CAL-
ALLED OUT IN BAC 5602.

PSD TO BAC 5602 IS NOW BEING PROCESSED TO COVER THIS SITUATION.

HE BOEING CO BARONNE W G SMITH 5-7512 LH-31

DEWIC C314

Attachment d

ALUMINUM COMPANY OF AMERICA

1309 WHITNEY BANK BUILDING

NEW ORLEANS, LOUISIANA 70130

(504) 572-3372

R. L. GERDETZ, Branch Sales Manager

ALCOA

February 8, 1974

Mr. Peter Hinkeldey
Martin Marietta Corp.
P. O. Box 29304
New Orleans, Louisiana   70129

Dear Pete:

Attached is a copy of Paul Mehr's letter to me of 1/30/74
plus the other data which you have been requesting through
me .

I believe you can fully appreciate Paul's comments with re-
gard to the proprietary nature of our capabilities.

I plan to get together with you next week to discuss the
question in Paul's last paragraph.

Yours very truly,

R. L. Gerdetz

RLG:BBN

Attachment

FROM PAUL L. MEHR
APPLICATION ENGINEERING DIVISION
NEW KENSINGTON

TO MR. R. L. GERDETZ

NEW ORLEANS

January 30, 1974

RE: MARTIN-MARIETTA AEROSPACE

Per L. W. Mayer's telegram of January 16, 1974, and your telegram of January 16, 1974, enclosed herewith is the following information:

1. Four copies each of full range stress-strain curves for 2219-T81 and T87 sheet, and 2219-T351, T37, T851 and T87 plate

2. Aging curves for 2219 material as follows:

    Natural aging of 0.064" thick 2219-T42 sheet
    Natural aging of 0.064" thick 2219-T37 sheet
    Artificial aging of 2219-T42 sheet and T4 forgings
    Artificial aging of 2219-T31 products
    Artificial aging of 2219-T37 products
    Artificial aging of 2219 sheet, cold worked 20% after
      quenching
    Effect of cold work on strengths of 2219 artificially
      aged at 375°F

We had also promised Pete Hinkeldey that we would provide general guidelines on Alcoa plate stretching capabilities. Enclosed herewith are these general guidelines which have been provided by Mr. H. W. Green based on current data supplied by Davenport. You will note that we consider this information to be proprietary and would request that Mr. Hinkeldey treat this information as such.

I would also be interested in the current status of the Space Shuttle External Tank program at Martin Marietta. Is there any additional information that is required? Has Martin Marietta established the basic External Tank design; and if so, we would appreciate reviewing the various components to make sure that everything is within Alcoa's current capabilities.

PAUL L. MEHR

PLM:jp

cc: ATC-TID
L. W. Mayer, Pittsburgh 27
J. A. Schroeder, Pittsburgh 27
H. W. Green, Pittsburgh 4
J. P. Willard, AED, New Kensington
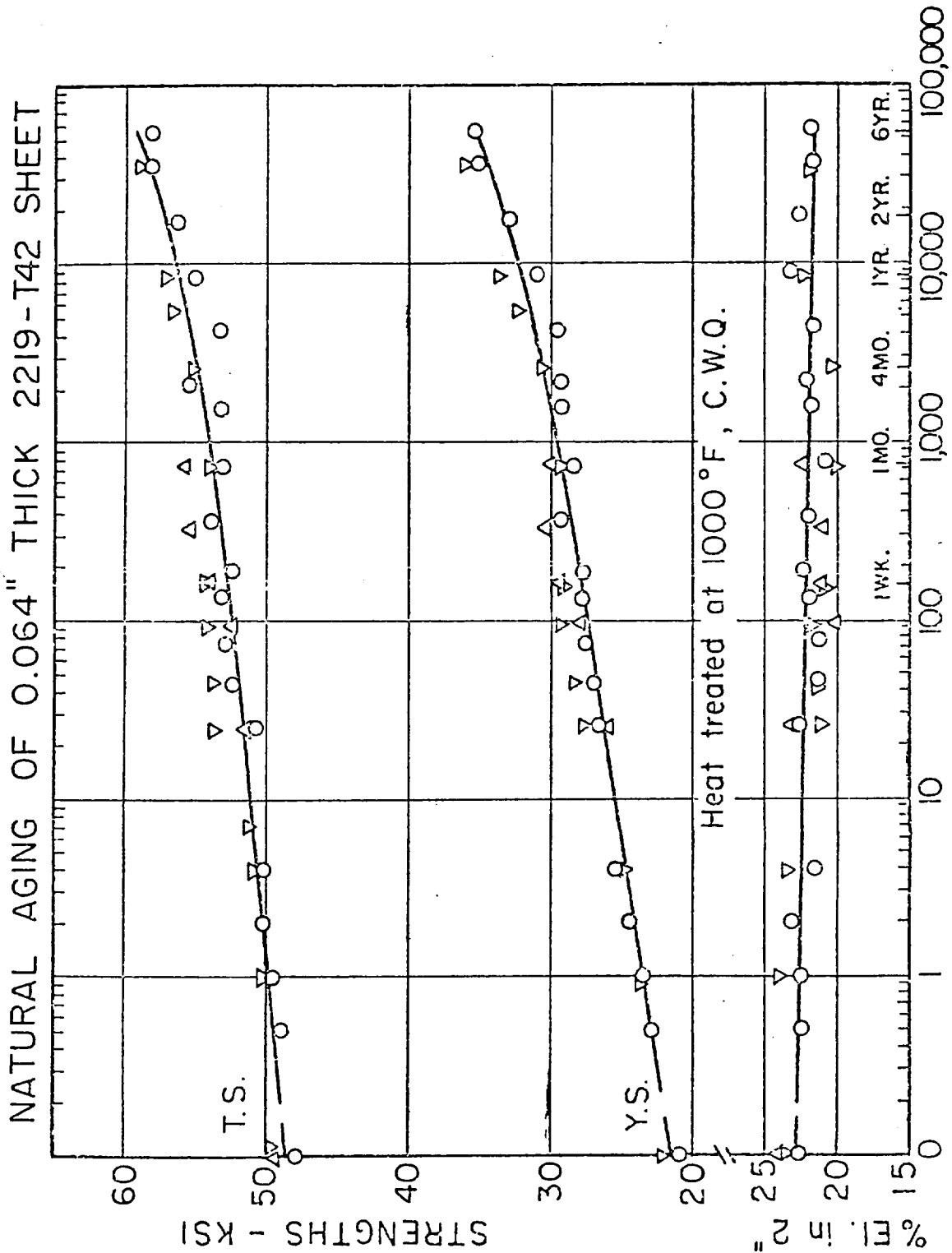File routed to E. H. Spuhler and E. W. Johnson

RECEIVED
ALCOA - NEW ORLEANS

FEB

RLG_____ CJL _____
JMC_____ B2H_____

NATURAL AGING OF 0.064" THICK 2219-T42 SHEET

Heat treated at 1000°F, C.W.Q.

Figure 1

NATURAL AGING OF 0.064" THICK 2219 SHEET

Heat treated at 1000°F, C.W.Q.
T37 Cold worked 8% after quenching.

Figure 3

Aging Time at Room Temperature - Hours
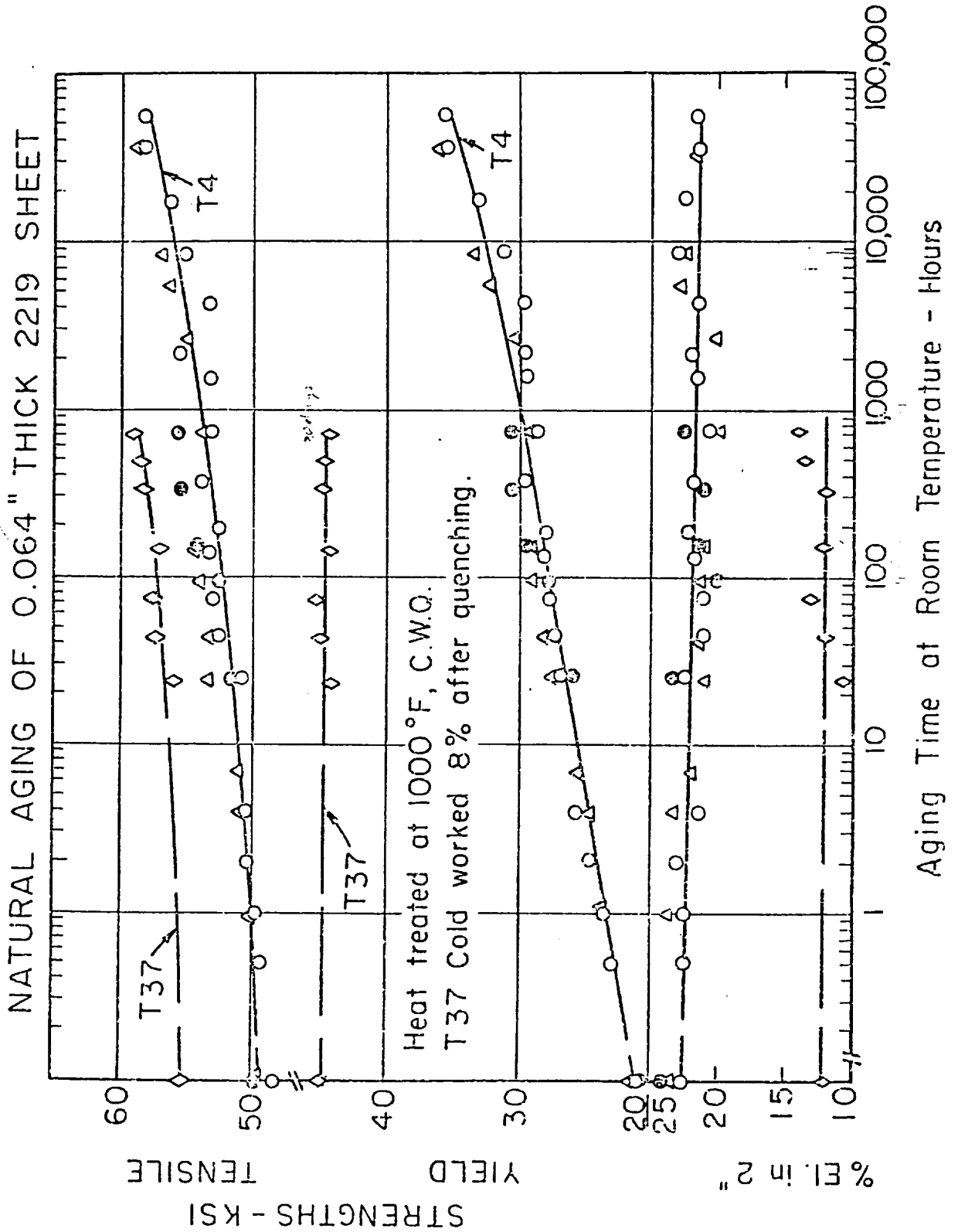
STRENGTHS - KSI
TENSILE   YIELD   % El. in 2"

ARTIFICIAL AGING OF 2219-T42 SHEET AND T4 FORGINGS

FIGURE 4

ARTIFICIAL AGING OF 2219-T31 PRODUCTS

PRODUCT	T31 PROPERTIES			TEMPERATURE
	TS KSI	YS KSI	% EL	
SHEET 0.064-0.125	55	39	18	ALL
PLATE 0.250-2.00"	56	36	25	ALL
EXTRUSIONS	49	32	26	350°F
TUBING	54	33	20	350°F
ROLLED ROD	56	35	28	300° & 350°F
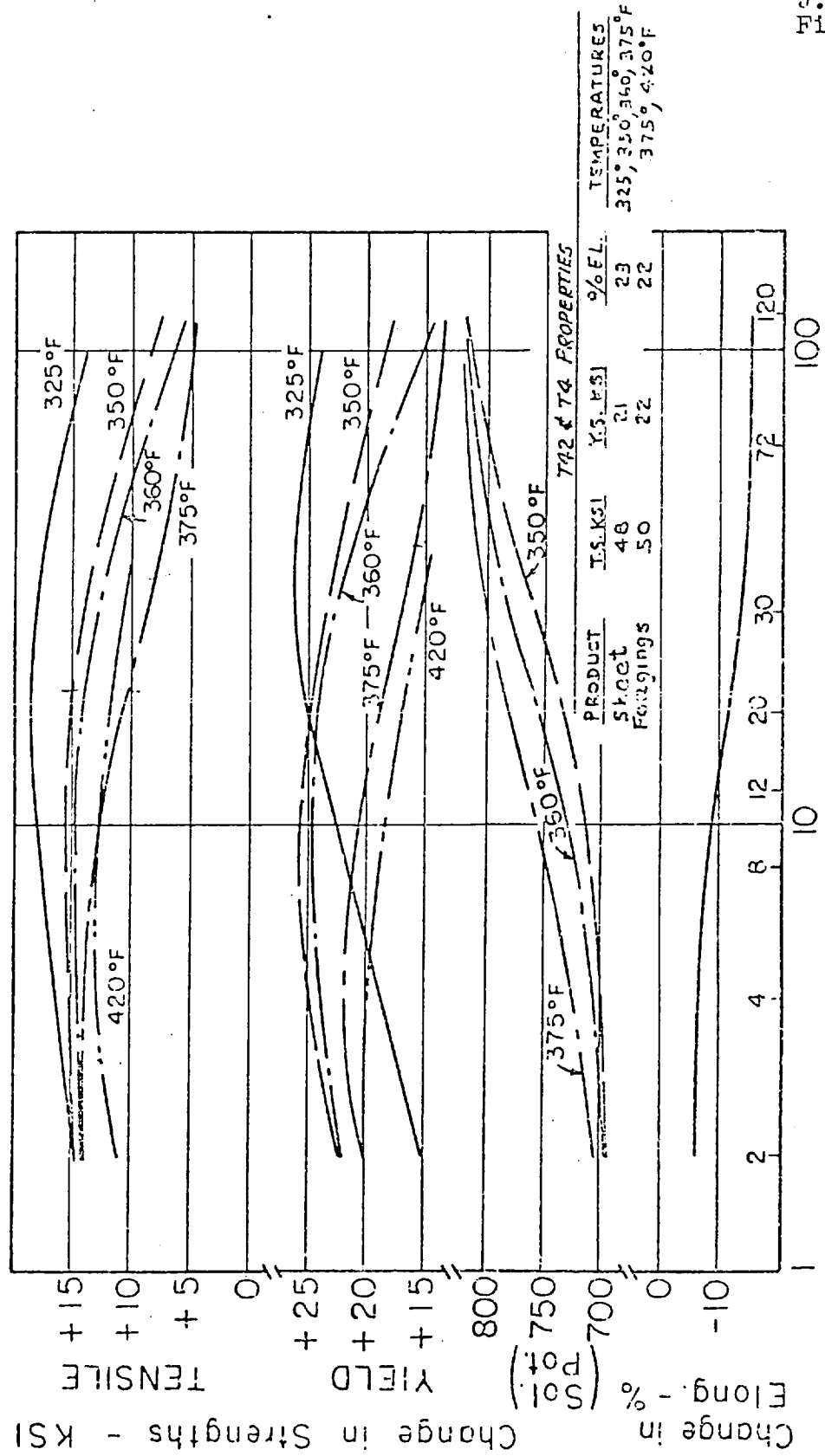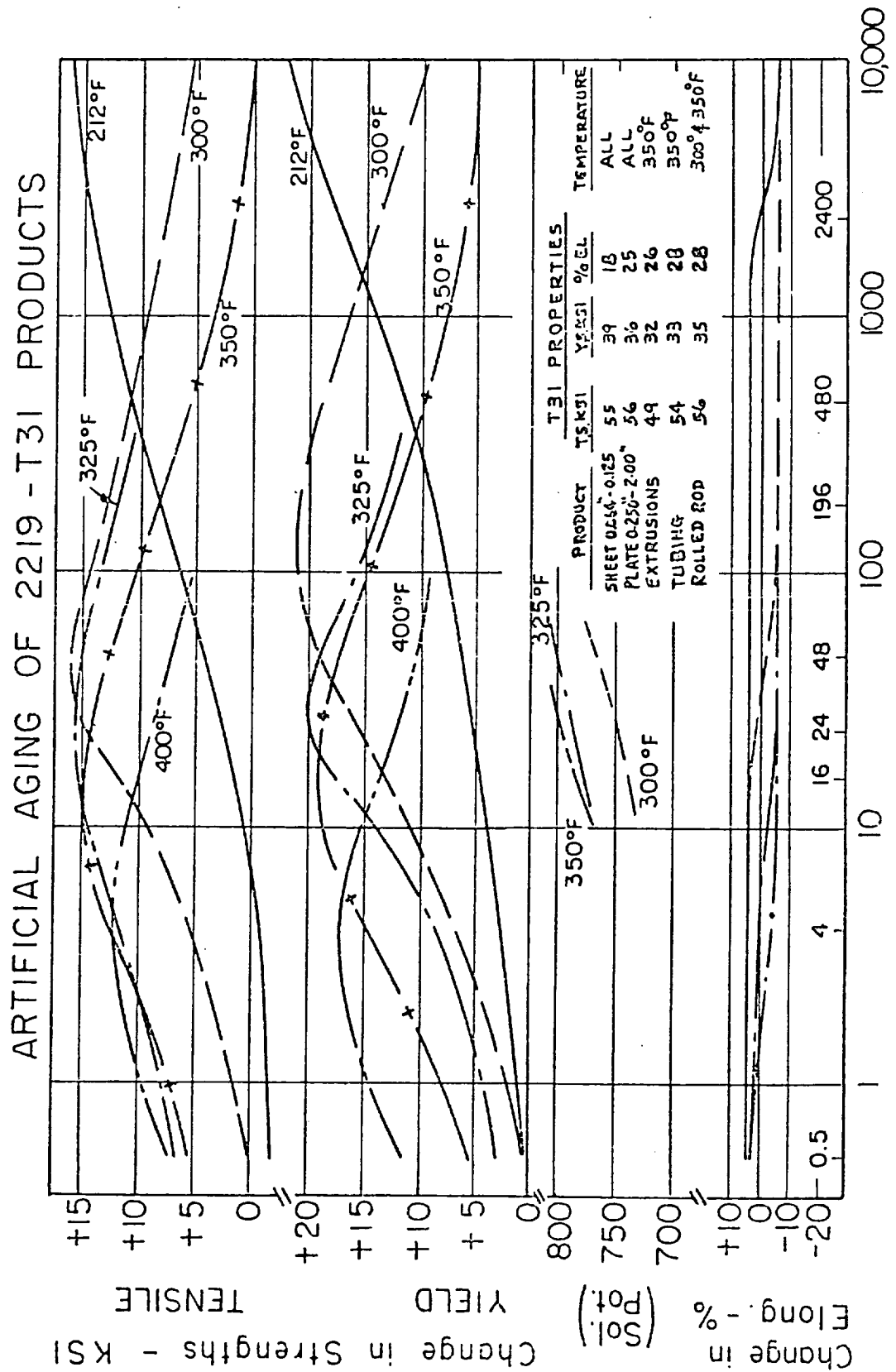
Aging Time - Hours

FIGURE 5
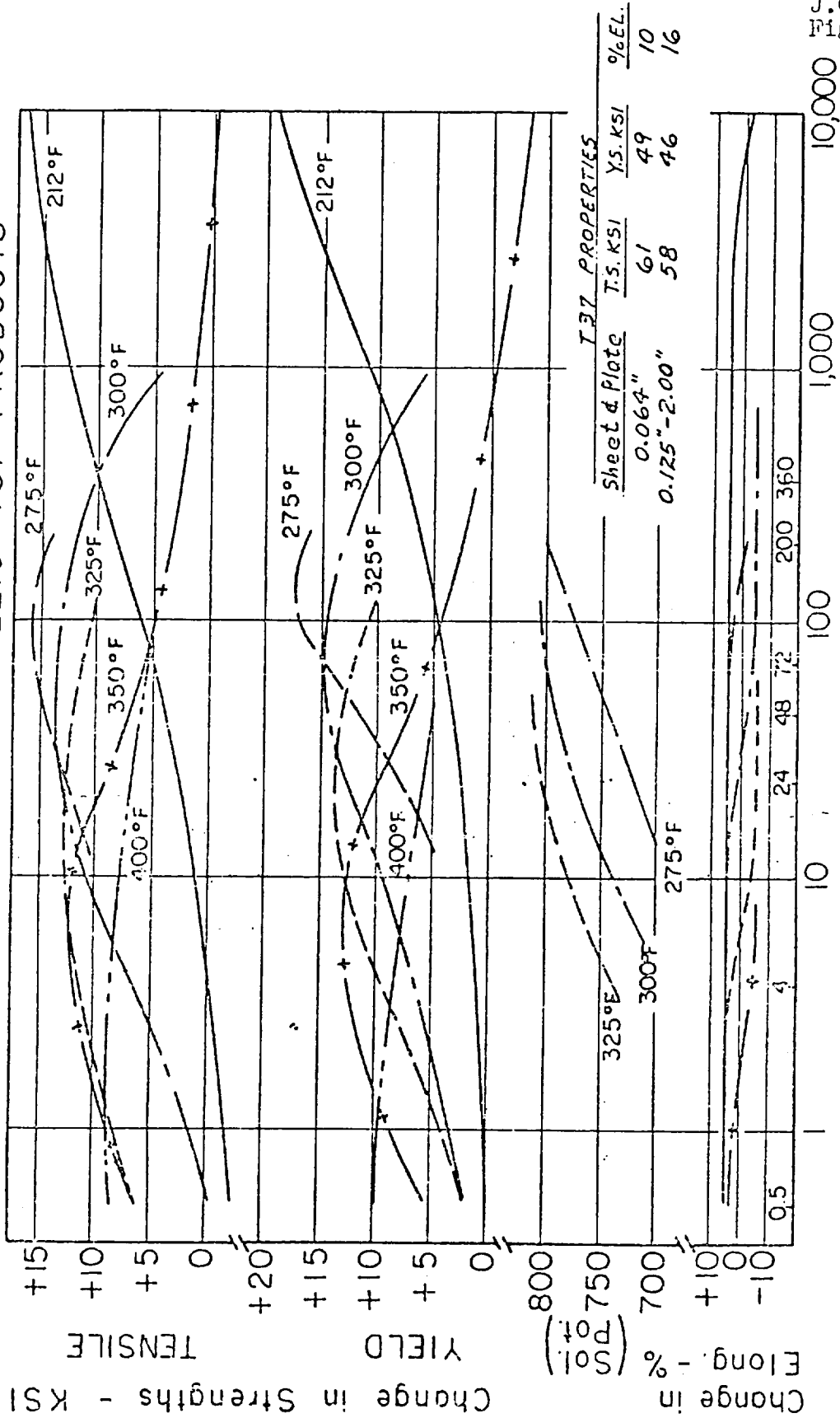
Change in Strengths - KSI

TENSILE

YIELD (Sol.) (Pot.)

Change in Elong - %

ARTIFICIAL AGING OF 2219-T37 PRODUCTS

FIGURE 7

ARTIFICIAL AGING OF 2219 SHEET
COLD WORKED 20% AFTER QUENCHING

ORIGINAL -T3 PROPERTIES

T.S.- ksi	Y.S.- ksi	El-%
63.1	51.1	9.0

EFFECT OF COLD WORK ON STRENGTHS
OF 2219 ARTIFICIALLY AGED AT 375°F

Sheet aged 18 hrs. at 375°F

Forgings aged 12 hrs. at 375°F

Tensile

Yield

Strengths - ksi

Percent cold work after quenching
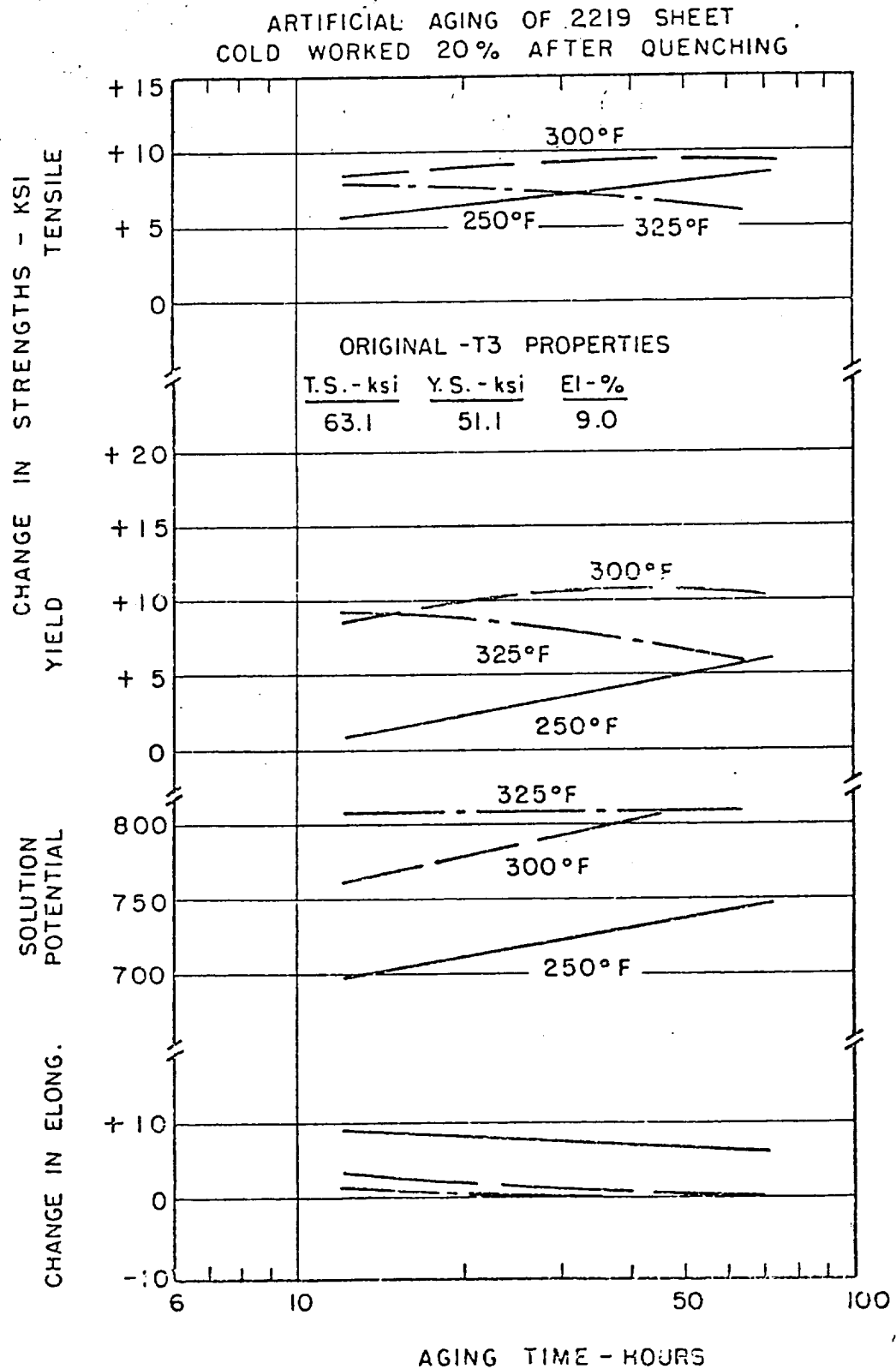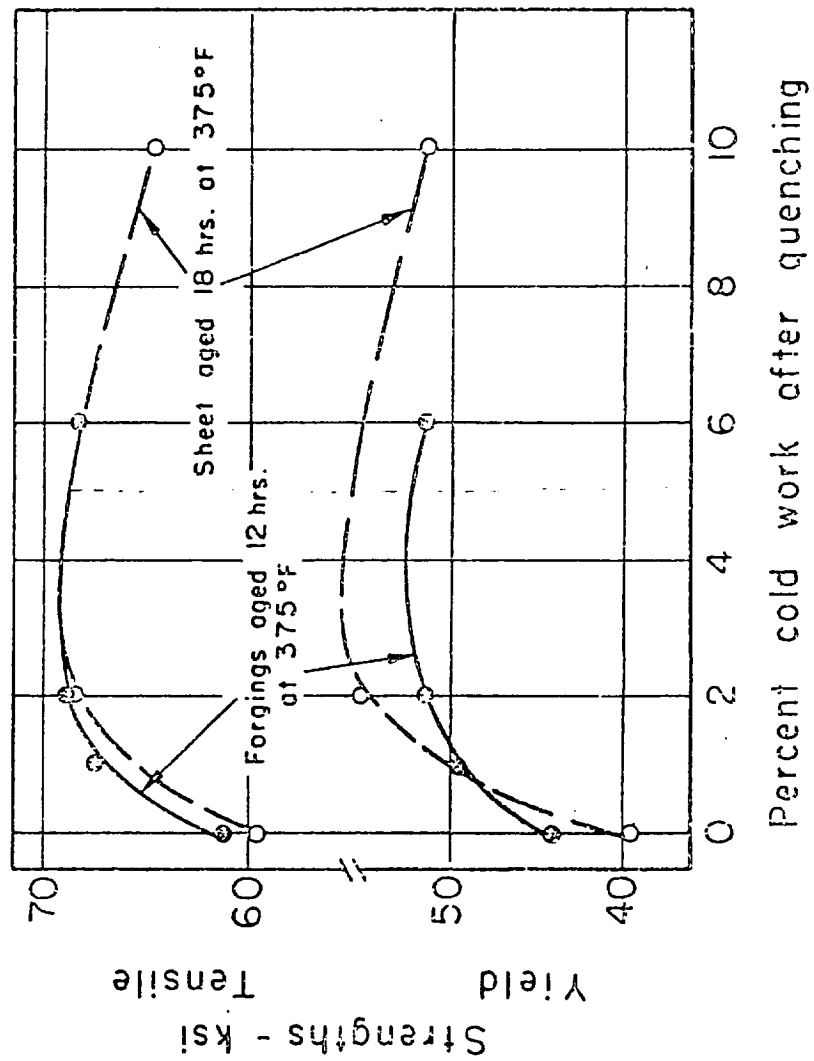
FIGURE 9

HVIS-4153-16

To: Dr. Michael Bjorkman   Boeing 2-H82C JR34

CC: Greg Olsen   NASA-MSFC
            Eric Christiansen NASA-JSC

From: Norman Elfer   Martin Marietta MAF 4153

Subject: SD_SURF Conclusions

Reference: Letter from M. Bjorkman to G. Olsen "Number of Elements Required to
            Make a BUMPER Model." 6/22/92 2H82C-GBR-295-92. Attached with
            annotations.

Your memo regarding SD_SURF is completely correct regarding how SD_SURF
operates. However, I would like to address the concerns about the conclusions to be
drawn from SD_SURF output and what modifications would be useful.

I did **not** mean to imply the conclusions attributed me in the two references. In fact, I
meant to completely avoid the subject of specific analyses in both the user's guide and
the AIAA paper, and I apologize for apparently leaving it open to having those
conclusions drawn.

The "wave" issue was not meant to be a criteria for judging an analysis, but rather a
guide for understanding how the ballistic limit surface was being queried by the
GEOMETRY output and the overall effect on PNP. The SD_SURF output shows which
velocities and obliquities influence the overall PNP.

The first conclusion you listed is a misquote. The correct quote from the paper is:

> ... the analysis of a curved surface in BUMPERII is **more** accurate [**than
> SD_SURF**] only if the size of the facets is smaller than the five-degree
> increments used on the RESPONSE and AREA SURFACE tables.

The missing word was "more," and it was used in relation to SD_SURF. This was only
meant to be a relative comparison between the two programs. The programs will
produce slightly different results that are negligible for the ballistic limit surfaces we
have dealt with. The remark addressed the angle subtended by a facet used to
represent a curved surface. The remark was meant to quantify a situation where the
BUMPERII result would be more accurate, **if** there was a significant difference in the
results. The point of the statement was that SD_SURF overall probability calculations
may be used as confidently as BUMPERII for models that have coarser increments than
5° facets and 90 threat directions, regardless of the ballistic limit surface. Finer models
are prohibitively time consuming and will not necessarily produce a different result.

1

The second conclusion you mention is that 45 threats are not sufficient to calculate the overall PNP. I did not say this, and regret that is conclusion could be drawn. For the current velocity distribution and space station shields, 45 threats is certainly adequate.

What causes errors? Like any computer model that treats a continuous process as a discrete or finite element, there is a chance of introducing errors. Of course, BUMPERII and SD_SURF do not require the same level of debugging as a finite element or hydrocode model. One sources of potential error is in the shadowing and area calculation, which BUMPERII does quite well. The partial shadowing option is a good quick way to determine if the discretized environment and geometry affect the effective area. The second potential source of error is how well the ballistic limit surface is interrogated. The old meteoroid method of using the average impact velocity is certainly inappropriate for space debris.

Your enclosures 4 and 5 give the false impression that BUMPERII averages over the the entire velocity range associated with each threat. In actual fact BUMPERII uses only a single velocity for each threat as shown in your enclosure 3. BUMPERII does not know what happens to the ballistic limit surface between each calculated threat velocity.

If the ballistic limit surface is smoothly varying there is potentially a small error introduced by lumping all of the exposed area of a curved surface into one flat facet and the debris angular distribution into a discreet number of threats. Each velocity and facet treats all of the exposed area as if it occurs at one velocity and obliquity. This is a relatively small error, the magnitude of which depends on the curvature of the ballistic limit surface.

However, if the velocity and obliquity increments are large, and the ballistic limit surface has deep troughs or sharp peaks, then a larger error is possible. It is possible to miss key areas. In other terms, the ballistic limit surface can be undersampled. What matters to the analyst is whether it affects the result. The shape of the ballistic limit surface has a direct impact on the fidelity of the environment and geometry models needed to sample it. The SD_SURF output provides the information to judge whether the cusps in the ballistic limit surface were caught by the model and whether they will influence the PNP.

Are 45 threats adequate for Space Station models? The answer is definitely "yes" for the current single bumper with MLI configuration. Reference to the SD_SURF The PNP is dominated by high velocity penetration resistance, where the ballistic limit surface is relatively smooth and there are more velocity increments.

However, this is not necessarily true for other ballistic limit surfaces. The PNP for the multi-shock shield is more sensitive to the low velocity performance. In this case, 45 threat increments may give slightly different results than environment models with more threats.

Are 15° degree facets adequate for Space Station models? The answer is again "yes" for the current single bumper with MLI configuration, but the facet size is closer

2

to being critical than the number of threat directions. The environment was modeled in 4° increments but the geometry is in 15° increments. Is it acceptable to only sample the ballistic limit surface at 30°, 45° and 60°? or 38°, 53° and 68°? This is what BUMPERII is doing using 15° facets. This appears to be adequate for the current shield design (especially considering our knowledge of obliquity effects at high velocities). The "waves" in the obliquities (calculated by GEOMETRY) are not necessarily in sync with a trough in the ballistic limit surface, so some averaging will occur. More importantly, as in the previous question, the PNP is dominated by high velocity penetration resistance where the ballistic limit surface is relatively smooth.

If the trough in multi-shock shields is significant at high velocities and obliquities, then the probability of one or more penetrations should be sensitive to the angle subtended by each facet.

As a point of interest, an alternative to building a more refined model for PNP comparison would be to rotate the geometric elements to watch the impact on PNP. This can be done using SuperTab and BUMPERII, or using the EXCEL AREA_MAKER Macro in SD_SURF.

One remark about the conclusion paragraph in your memo: I take it you were referring to the probability of one or more penetrations (1-PNP) when you stated that "facets subtending 15° angles give mean numbers of impact accurate to within a fraction of a percent." The number of impacts should be accurate, the question is whether or not the impacts will penetrate, which of course depends on the velocity and obliquity of impact, as well as the ballistic limit surface.

How should SD_SURF operate? As SD_SURF is currently structured, it accurately shows how BUMPERII queries the ballistic limit surface. However, as your memo drives home, it can be somewhat confusing. It was assumed that the analyst would have to try grouping velocities and obliquities in several ways (easily done in EXCEL) to completely understand which velocity and obliquity combinations are most significant to giving the overall PNP.

There are several approaches to enhancing the utility of SD_SURF but I view them as enhancements rather that errors in the current implementation.

The first possibility is to lump all of the area of a facet into the closest velocity and obliquity cell. This smooths out the peaks for a single facet (but there will still be spurious peaks when different facets are close). This would also introduce unnecessary error into the overall PNP analysis.

The second possibility will simplify interpretation and still maintain consistency with BUMPERII. The final results can be rolled up into 1 km/s and 5° increments. The EXCEL AREA_MAKER already takes A_SURF output and puts the areas into 0.5 km/s increments instead of the 0.25km/s increments used by RESPONSE. This will remove some of the "waves" in the velocity direction, but not in the obliquity direction, since they were introduced by 15° facets. Your enclosure 4 illustrated the problem of splitting up the exposure areas in one dimension (velocity). The requirement to split up the area

3

in velocity and obliquity will still create some interpretation problems. Due to these problems, the analyst must still exercise some judgement, so that this change would not make a significant impact.
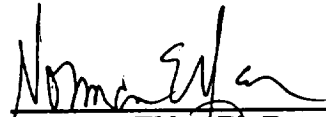
Another option is for A_SURF to spread the areas associated with each facet over the velocity and obliquity range dictated by the number of threats and the facet size used to model curved surfaces. The first number is available from the GEOMETRY output, while the second would have to be entered manually. This would help cure the problem of undersampling the ballistic limit surface (just as partial shadowing makes up for a a coarse geometry model). It should also be noted that this same approach is feasible with the SHIELD portion of BUMPERII (or BUMPERIII?) For example, a facet with a 38° obliquity to a particular threat could be assumed to have areas at 33°, 38° and 43° degrees to a given threat direction. (The next level of refinement is to partition the area according to projected areas based on obliquity.) (This averaging feature should be selectable by PID or location, since it is inappropriate for a flat surface like a cupola pane, unless you want to include elliptical orbits into the analysis as well.) Perhaps if this would be first implemented as an enhancement to BUMPERII, it is more politically acceptable.

The benefits of these options need to be evaluated by NASA to see if it is worth continuing the development of SD_SURF in conjunction with, or separately from, BUMPERII.

If you have additional comments on SD_SURF of if I may be of assistance please call me at (504)-257-3162. My FAX is (504)-257-4440.

My address is: Norman Elfer
Dept 4153
Martin Marietta Manned Space Systems
P.O. Box 29304
New Orleans, LA 70189

Norman Elfer, Ph.D.
Metals Group Lead

PS. As I mentioned to Greg Olsen, the Macintosh version of BUMPERII may produce errors. Apparently BUMPERII has sections of code that pass an R*8 variable to a subroutine that expects an R*4 variable or vice versa. This is not an uncommon procedure, but the Macintosh will produce an error (using both Language Systems FORTRAN and Absoft FORTRAN). Could that have caused the apparent conflict between your enclosure 5 and 6? Something appears to be wrong (at least with the velocities less than 5 km/s) if enclosure 6 is supposed to be the same as enclosure 5. Was the environment distribution included with the projected area when making enclosure 6? - N.E.

4

June 22, 1992
2H82C-GBR-295-92

To: G. Olsen   MSFC/ED-52

cc: R. Abbott   JR-34
              D. Williams   JR-34

Subject: Number of Elements Required to Make a BUMPER Model.

Reference: 1)   N. Effer et al. "Space Debris Surfaces (Computer Code):
                    Probability of no penetration vs impact velocity and obliquity."
                    AIAA Space Programs and Technologies Conference, 24-
                    27 March 1992. AIAA 92-1407.

              2)   N. Effer, "User's Guide for Space Debris Surfaces
                    (SD_SURF) FORTRAN Applications and EXCEL Macros
                    and Spread Sheets." February 1992.

Recently, NASA/MSFC placed Martin-Marietta under contract to, among other things,
write a post-processor for BUMPER (References 1 and 2). Among the conclusions made
from this work were:

1.   "... the analysis of curved surface in BUMPER II is accurate only if the size
      of the facets is smaller than the five degree increments used on the RESPONSE
      tables."

2.   The default 45 orbital debris threats used by BUMPER are too few.

These conclusions were in part based on the analysis of the effective area of a flat plate
whose normal points is the direction of the y-axis. These SD_SURF results are shown
plotted in Enclosure 1. The objectionable features of these plots are the waves on the
surface labeled "waves" in Enclosure 1. The author of the reference was only able to
smooth out the waves in the SD_SURF plots when the GEOMETRY model of a curved
surface target used facets which subtended an angle of less than 5° (Conclusion 1) and
numbers of threats equal to 68 (Conclusion 2).

The author of the present memo was unaware of ever having seen the waves of References
1 and 2 before. To illustrate this, the problem of Enclosure 1 was calculated and plotted by
the present author in Enclosure 2. Note that there are no waves and the trends are smother
but somewhat similar to those of Enclosure 1.

This discrepancy led to a closer examination of the plotting procedure used in Reference 2.
It was discovered the waves are solely a function of the plotting procedure and are not a
feature of the BUMPER II GEOMETRY tables.

GEOMETRY defaults to 45 equally spaced threat approach angles. Since there is a one-to-
one mapping between orbital debris approaching angle and closing velocity, this results in
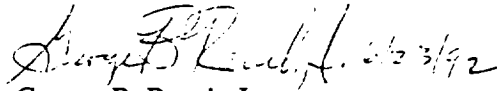
unequal spacing of the threats in velocity space, See Enclosure 3 top row of squares. The 3d plotting routine used by EXCEL required evenly spaced intervals of velocity. The intervals used by SD_SURF are illustrated by the bottom row of squares in Enclosure 3. Note that for small closing velocities there are many SD_SURF intervals for one GEOMETRY interval.

The one dimensional analog of the algorithm used by SD_SURF to distribute effective area belonging to the unequally spaced GEOMETRY intervals over the equally spaced SD_SURF intervals is illustrated in Enclosure 4. Note that the SD_SURF algorithm introduces large gaps in the plot by assigning all of GEOMETRY effective area to the SD_SURF interval nearest the center of the GEOMETRY interval. Thus, if there are many SD_SURF intervals per GEOMETRY interval some of the SD_SURF intervals will never get an effective area assigned to them. That is, waves on the results will appear. To illustrate the effect, the effective area calculation for the flat plate of Enclosure 1 and 2 was plotted in Enclosure 5 using the GEOMETRY intervals. The SD SURF algorithm was used to replot the data on evenly spaced intervals in Enclosure 6. Note the waves.

In conclusion, the waves are an artifact of SD_SURF and not GEOMETRY. Other studies have shown that facets subtending 15° angles give mean numbers of impact accurate to within a fraction of a percent. The conclusion made in References 1 and 2 that 5° facets are necessary is solely a consequence of using 5° and 0.25 km/s intervals in SD_SURF.
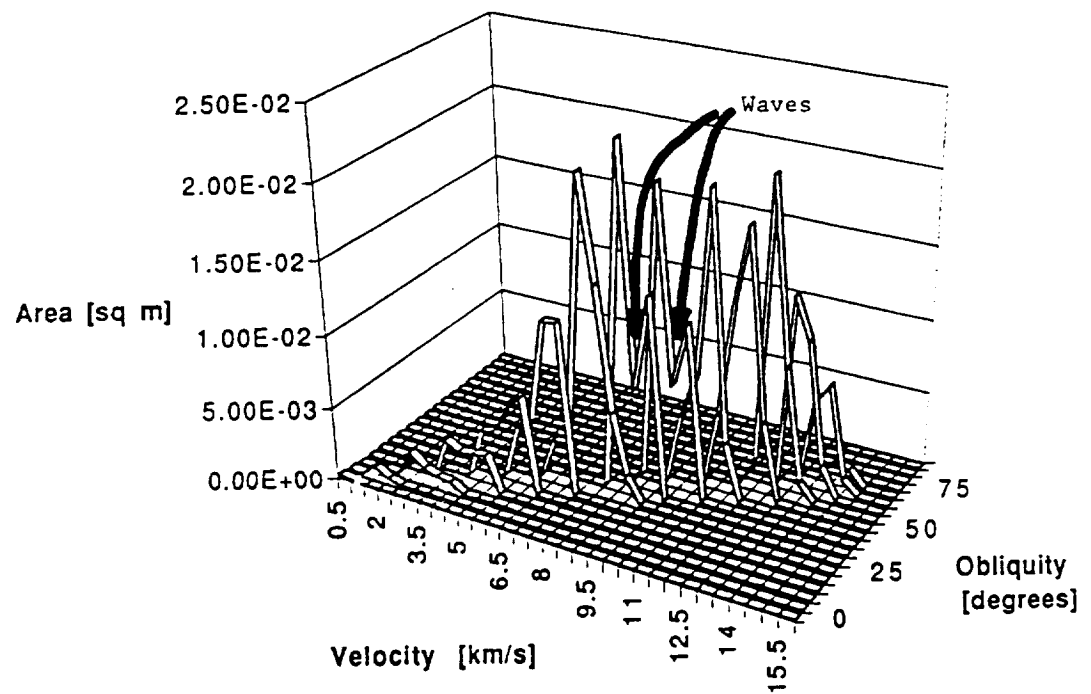
M. D. Bjorkman
2-H82C   JR-34
461-5788

George B. Rauch, Jr.
2-H82C   JR-34
461-5755
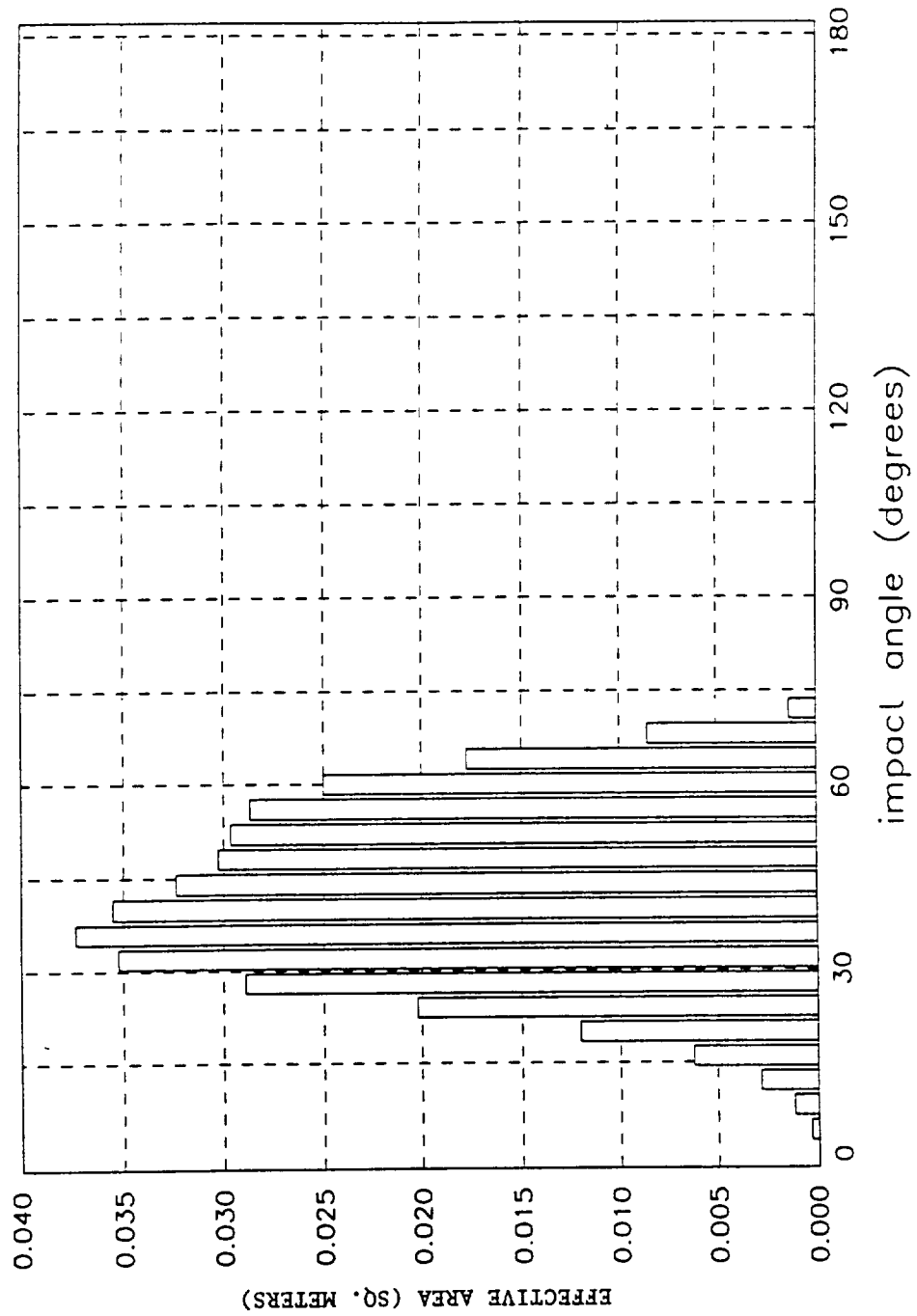
MDB:am

ENCLOSURE 1

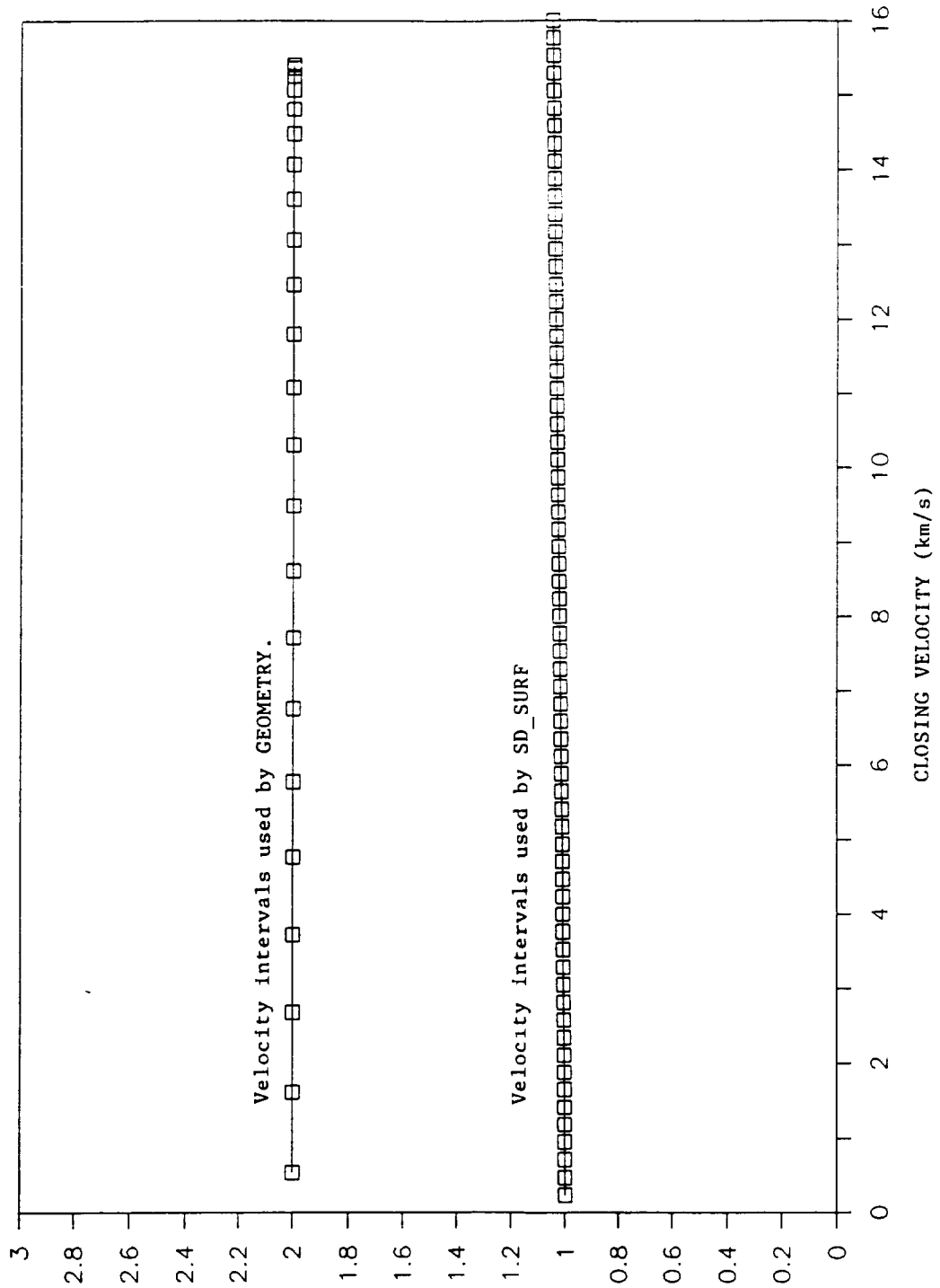EXAMPLE OF WAVES WHICH APPEAR ON AN SD_SURF PLOT OF
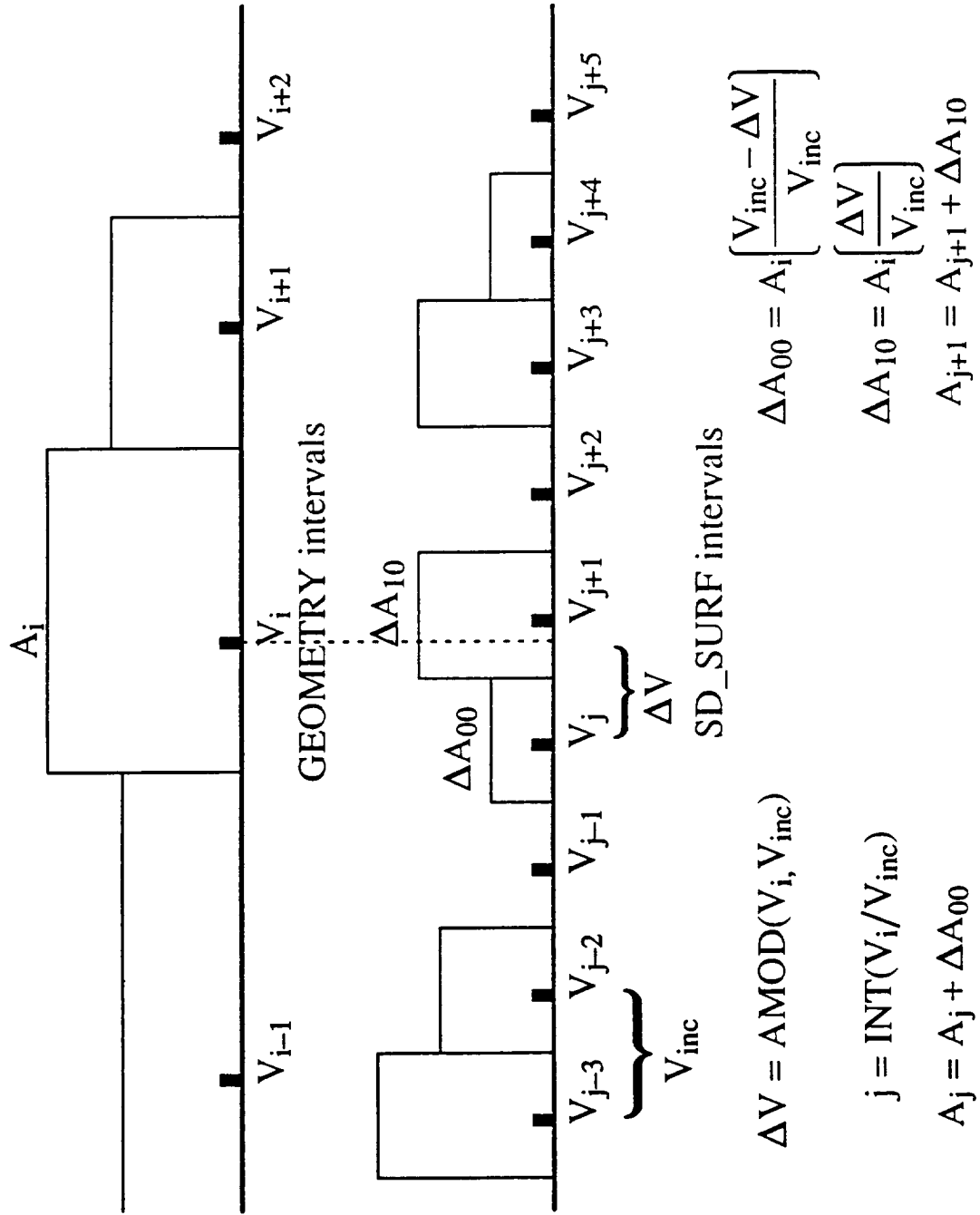A BUMPER GEOMETRY FILE.

39

ENCLOSURE 2

EFFECTIVE AREAS CALCULATED WITH BUMPER. NOTE THAT THE PLOT IS SMOOTH WITH NO "WAVES".
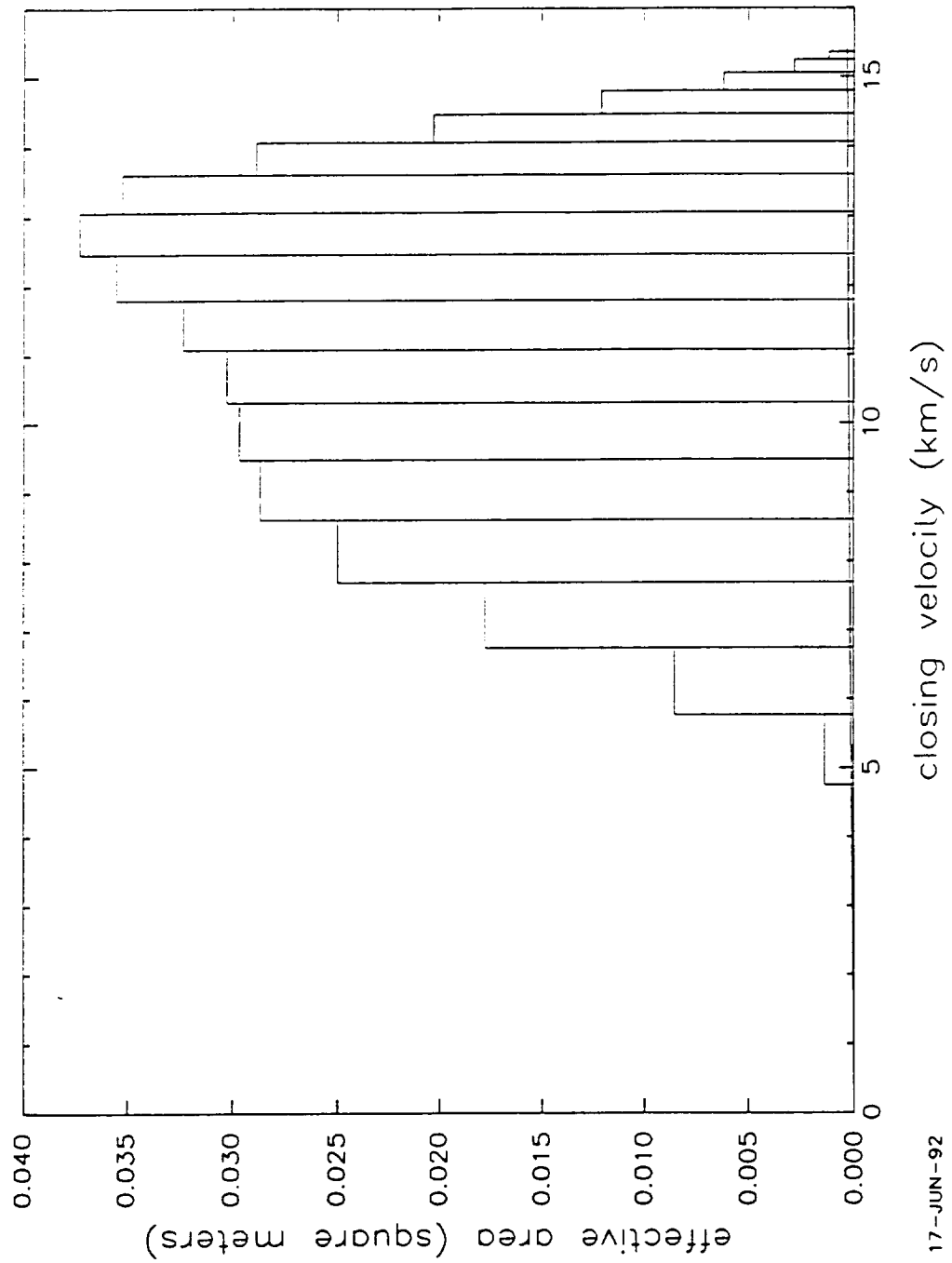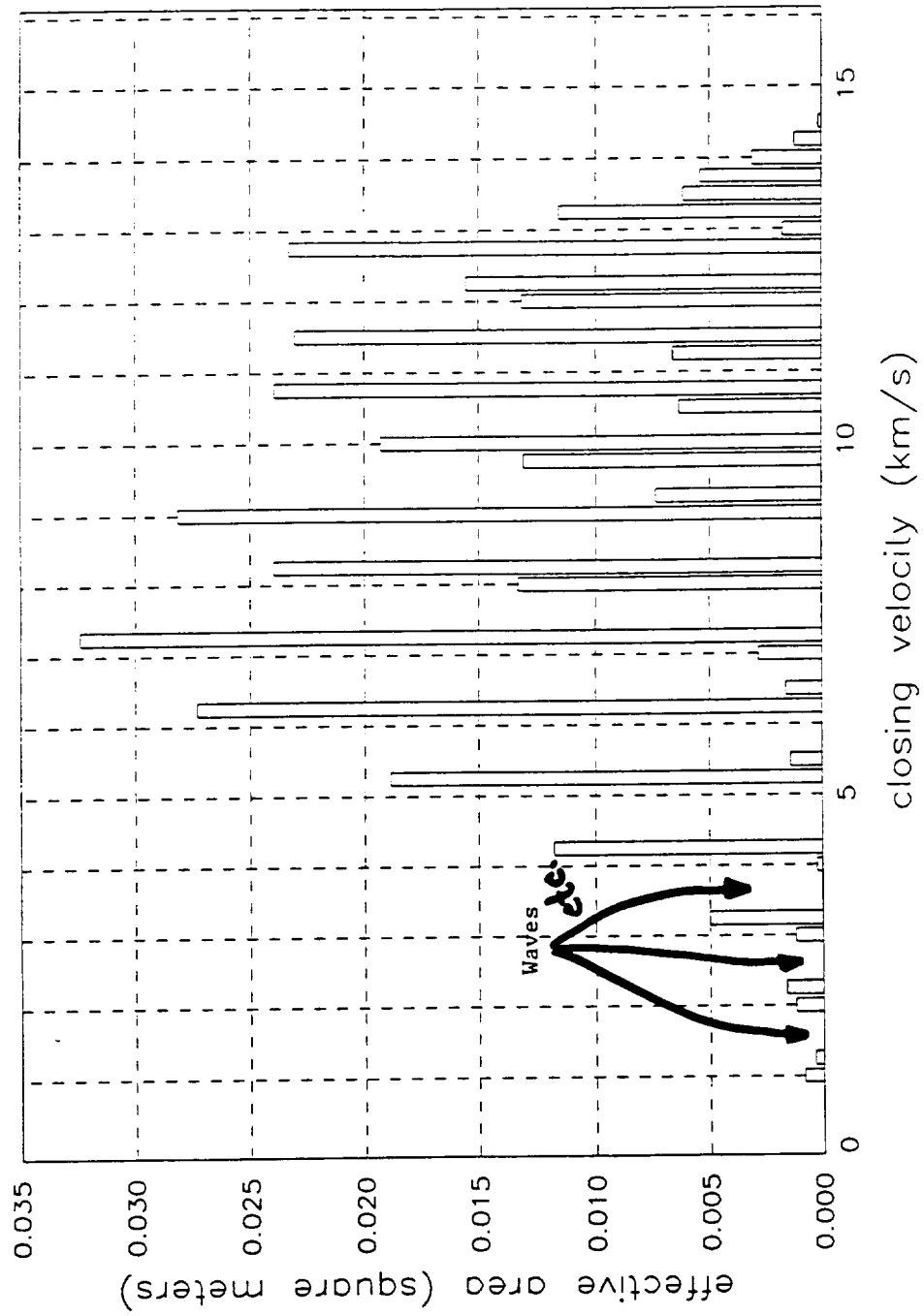
10-JUN-92

ENCLOSURE 3

COMPARISON OF THE SIZE OF THE VELOCITY INTERVALS USED BY THE GEOMETRY PREPROCESSOR FOR BUMPER WITH THE VELOCITY INTERVALS USED FOR PLOTTING BY SD_SURF.

V_{i-1} V_i V_{i+1} V_{i+2}

A_i

GEOMETRY intervals

V_{j-3} V_{j-2} V_{j-1} V_j V_{j+1} V_{j+2} V_{j+3} V_{j+4} V_{j+5}

SD_SURF intervals

ΔA_{10}

ΔA_{00}

ΔV

V_{inc}

$$\Delta V = \text{AMOD}(V_i, V_{inc})$$

$$j = \text{INT}(V_i / V_{inc})$$

$$A_j = A_j + \Delta A_{00}$$

$$\Delta A_{00} = A_i \left[\frac{V_{inc} - \Delta V}{V_{inc}} \right]$$

$$\Delta A_{10} = A_i \left[\frac{\Delta V}{V_{inc}} \right]$$

$$A_{j+1} = A_{j+1} + \Delta A_{10}$$

1

ENCLOSURE 5.

closing velocity (km/s)

effective area (square meters)

17-JUN-92

EFFECTIVE AREAS CALCULATED WITH BUMPER PLOTTED AS A FUNCTION OF CLOSING VELOCITY. NOTE THAT THE PLOT IS SMOOTH WITH NO "WAVES", JUST AS THE SAME DATA PLOTTED AS A FUNCTION OF APPROACH ANGLE WERE IN ENCLOSURE 2.

ENCLOSURE 6

1 sq. meter plate facing y-direction
45 threats. 10 sub intervals

17-JUN-92

THE SAME DATA AS ENCLOSURE 5 PLOTTED WITH THE SD_SURF ALGORITHM. NOTE THAT THE SD_SURF PLOTTING
ALGORITHM HAS INTRODUCED "WAVES" INTO THE PLOT.